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6. AUTHORS
Ramesh Rao, B.S. Manoj, Michele Zorzi

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The Regents of the Univ. of Calif., U.C. San Diego
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14. ABSTRACT
The specific aims of the project include: (i) to propose a Cognitive Network concept by applying the cognition loop both to the in-stack (from MAC to Transport layer) and the out-stack parameters using probabilistic graphical models and (ii) to create opportunistic solutions for cross layer cognitive networking. We propose to use a novel approach based on Bayesian Networks (BNs) that can capture the dependency between network protocol parameters across the stack exploiting the historical behavior of the observed data. We also proposed and

15. SUBJECT TERMS
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a. REPORT	b. ABSTRACT	c. THIS PAGE			Ramesh Rao
UU	UU	UU	UU		19b. TELEPHONE NUMBER: 858-822-4572

Report Title

Final Progress Report: A research proposal on Cognitive Opportunistic Communications and Cognitive Cross-layer Protocol Stack Design

ABSTRACT

The specific aims of the project include: (i) to propose a Cognitive Network concept by applying the cognition loop both to the in-stack (from MAC to Transport layer) and the out-stack parameters using probabilistic graphical models and (ii) to create opportunistic solutions for cross layer cognitive networking. We propose to use a novel approach based on Bayesian Networks (BNs) that can capture the dependency between network protocol parameters across the stack exploiting the historical behavior of the observed data. We also proposed and prototyped a Cognitive Access Point (CogAP) that utilized the out- stack BN model. Furthermore, we investigated cross layer solutions for implementing a distributed control channel and a neighbor discovery mechanism that is robust against jamming attacks, studying the problem both with a theoretical and a simulative approach. We concluded our work with a practical case of study, in which we observed the challenges in gathering network traffic information from an emergency response network and we studied three physical world events where we conducted passive network traffic measurements to study the interaction between physical and cyber worlds.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
2012/08/11 1	24	Alfred Asterjadhi, Michele Zorzi. JENNA: A JAMMING EVASIVE NETWORK-CODING NEIGHBOR-DISCOVERY ALGORITHM FOR COGNITIVE RADIO NETWORKS, IEEE Wireless Communications, (08 2010): 24. doi:
2012/07/23 2	25	Chetan Kumar Verma, Bheemarjuna Reddy Tamma, B. S. Manoj, and Ramesh Rao. A Realistic Small-World Model for Wireless Mesh Networks, IEEE Communications Letters, (04 2011): 455. doi:
2012/07/23 2	23	Nicola Baldo,Alfred Asterjadhi, Michele Zorzi. Dynamic Spectrum Access Using aNetwork Coded Cognitive Control Channel, IEEE Trans. Wireless Communication, (08 2010): 2575. doi:
2012/07/23 2	22	Marco Levorato, Urbashi Mitra, Michele Zorzi. Cognitive Interference Management inRetransmission-Based Wireless Networks, IEEE TRANSACTIONS ON INFORMATION THEORY, (05 2012): 3023. doi:
2012/07/23 2	21	Bheemarjuna Reddy Tamma, B.S. Manoj, Ramesh R. Rao. Traffic sensing and characterization in multi-channel wireless networks for cognitive networking, Computer Networks, (12 2011): 1968. doi:
2012/07/23 2	18	Riccardo Manfrin, Andrea Zanella, Michele Zorzi. CRABSS: CalRAdio-Based advanced Spectrum Scanner for cognitive networks, Wirel. Commun. Mob. Comput. , (11 2010): 1682. doi:

TOTAL: 6

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper	
2012/08/11 19	14	Yao Liu, Bheemarjuna Reddy Tamma, B. S. Manoj, Ramesh Rao. Traffic Prediction for Cognitive Networking inMulti-Channel Wireless Networks, infocom 2010. 2010/03/15 03:00:00, . : ,
2012/07/23 22	26	Riccardo Manfrin, Luca Boscato, Andrea Zanella, Michele Zorzi. CRABSS: CalRAdio-Based advanced Spectrum Scanner for cognitive networks, IWCMC 2010,. 2010/06/28 03:00:00, . : ,
2012/07/23 2	13	Bheemarjuna Reddy Tamma, B. S. Manoj, Ramesh Rao. An Autonomous Cognitive Access Point for Wi-Fi Hotspots, IEEE Globecom 2009. 2009/12/01 03:00:00, . : ,
2012/07/23 2	11	Alfred Asterjadhi, Federico Librino, Michele Zorzi. Analysis of Random Access Protocols for Multi Channel Wireless Networks, IEEE Globecom 2011. 2011/12/05 03:00:00, . : ,
2012/07/23 2	10	Giorgio Quer, Nicola Baldo, Michele Zorzi. Cognitive Call Admission Control for VoIP over IEEE 802.11 using Bayesian Networks, IEEE Globecom 2011. 2012/12/05 03:00:00, . : ,
2012/07/23 19	9	B. S. Manoj, Bheemarjuna Reddy Tamma, Ramesh R. Rao. On the Impact of Physical-Cyber world Interactions during Unexpected Events, ACWR'11, . 2011/12/18 03:00:00, . : ,
2012/07/23 19	8	B. S. Manoj, Bheemarjuna Reddy Tamma, Paul Blair, Ramesh Rao. On Non-invasive Network Measurement forEmergency Response Wireless Mesh Networks, Applications of Digital Information and Web Technologies (ICADIWT), 2011 Fourth International Conference on the. 2011/08/04 03:00:00, . : ,
2012/07/23 19	6	Alfred Asterjadhi, Raju Kumar, Thomas La Porta, Michele Zorzi. Broadcasting in Multi Channel Wireless Networks in the Presence of Adversaries, I IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks. 2011/06/27 03:00:00, . : ,
2012/07/23 19	5	oshal Daftari, Bheemarjuna Reddy Tamma, B. S. Manoj, Ramesh Rao. On Capturing Spatio-temporal Factors in Cognitive Network Channel Selection, IEEE 4th International Symposium on Advanced Networks and Telecommunication Systems. 2010/12/15 03:00:00, . : ,
2012/07/23 19	4	Bharathan Balaji, Bheemarjuna Reddy Tamma, B. S. Manoj. A Novel Power Saving Strategy for Greening IEEE 802.11 based Wireless Networks, IEEE Globecom. 2012/12/06 03:00:00, . : ,
2012/07/23 19	3	Giorgio Quer, Hemanth Meenakshisundaram, Bheemarjuna Tamma, B. S. Manoj, Ramesh Rao, Michele Zorzi. Cognitive Network Inference through Bayesian Network Analysis, IEEE Globecom. 2010/12/06 03:00:00, . : ,
2012/07/23 19	2	Yao Liu, Bheemarjuna Reddy Tamma, B. S. Manoj, Ramesh Rao. On Cognitive Network Channel Selection and the Impact on Transport Layer Performance, IEEE Globecom. 2010/12/06 03:00:00, . : ,
2012/07/23 19	1	Giorgio Quer, Hemanth Meenakshisundaram, Bheemarjuna R. Tamma, B. S. Manoj, Ramesh Rao, Michele Zorzi. Using Bayesian Networks for Cognitive Control of Multi-hop Wireless Networks, MILCOM 2010. 2010/11/01 03:00:00, . : ,

TOTAL: **13**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Joshal Daftari	0.35	
FTE Equivalent:	**0.35**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Bheemarjuna Tamma	0.04
Giorgio Quer	0.04
FTE Equivalent:	**0.08**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Ramesh Rao	0.06	
FTE Equivalent:	**0.06**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT SUPPORTED	Discipline
Dheeraj Navani	0.03	High school apprentices
FTE Equivalent:	**0.03**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Joshal Daftari
Total Number: 1

Names of personnel receiving PHDs

NAME
Giorgio Quer
Total Number: 1

Names of other research staff

NAME	PERCENT SUPPORTED
Manoj Balakrishnan, Research Scienti	0.07
Michele Zorzi, Visiting Researcher	0.11
FTE Equivalent:	**0.18**
Total Number:	**2**

Sub Contractors (DD882)

1 a. University of Padova

1 b. Department of Information Engineering
Via Gradenigo 6B
35131 Padova 00000

Sub Contractor Numbers (c): PO # 10304440 - SUB

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): Within the Subcontract awarded to the research group at the University of Padova, the research worl

Sub Contract Award Date (f-1): 9/1/2009 12:00:00AM

Sub Contract Est Completion Date(f-2): 8/31/2011 12:00:00AM

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Inventions (DD882)

Scientific Progress

In our work on the application of cognition loop on the protocol stack, published in the proceedings of IEEE GLOBECOM 2010 and IEEE MILCOM 2010, we used a probabilistic graphical modeling approach, Bayesian Networks (BNs), in order to create a representation of the dependency relationships between significant parameters spanning transport and medium access control (MAC) layers in single-hop and multi-hop wireless network environments. We made two key contributions: first, in single-hop networks, we created graphical models from historical data observed from the protocol stack and verified their usefulness and second, we created a BN consists of MAC and transport parameters and used that BN graph to estimate the possibility of network congestion. That is, we exploit our BN models to face one of the problems of the TCP protocol, which does not have any mechanism to infer when congestion occurs in the network and therefore waits till some packets are lost for reacting to congestion in the network. Such a reactive nature of TCP leads to wastage of precious network resources like bandwidth and power. With the help of BN structure derived from network environment and current network state, we showed how to infer in advance the congestion state of the network. Additionally, we constructed BNs for different network environments by sampling network parameters on-the-fly in simulated network environments. We found that it is possible to predict the congestion state of network with quite good accuracy given sufficient training samples and the current value of the TCP congestion window. Conclusions of our results on this direction include: (i) BN is a useful tool for cognitive networking to determine, represent and exploit the probabilistic dependencies and conditional independencies between protocol parameters, (ii) exploiting BN, we can design an inference engine to accurately predict the behavior of protocol parameters, and (iii) we can obtain useful insights on the influence of the data size used for training on the accuracy of network parameter behavior prediction.

This approach has been extended to out stack parameters in our work presented at IEEE ANTS 2010. Bayesian Networks (BNs) has been exploited for capturing the spatio-temporal factors in cognitive networks. In this work a BN makes use of historical network information to learn the network behavior across spatio-temporal-spectral dimensions and predicts best configuration for each Access Point (AP) in a Wireless LAN (WLAN) system. We further present the application of BNs for traffic prediction as well as channel selection in a cognitive WLAN scenario. Our results prove that the space and time are critical factors that can impact the performance of the network configuration. We noticed improvement in traffic prediction accuracy and channel selection accuracy, respectively, of 35% and 40%, when using space and time information.

In order to complete this line of research on cognitive networking, we analyzed also the traffic sensing and characterization block of our cognitive networking systemsin a work published in Elsevier computer Networks journal. We figured out that it is very challenging to perform traffic characterization in multi- channel multi-radio wireless networks. Due to the presence of network traffic in multiple channels, the existing count-based packet sampling methods demand continuous capture on each channel to be effective; this requires a dedicated wireless interface per channel, and hence the existing sampling methods require a very expensive infrastructure and have poor scalability. Time-based sampling methods, on the other hand, offer a cost-effective and scalable solution by reducing the amount and cost of the resources necessary to monitor and characterize the wireless spectrum.
The contributions of this work include the following: (i) a discussion of packet sampling techniques for traffic sensing in multi-channel wireless networks, (ii) a comparison of various time-based sampling strategies using the Kullback–Leibler divergence (KLD) measure, (iii) a study on the effect of the sampling parameters on the accuracy of the sampling strategies, (iv) development of sampling accuracy graphs for easing the process of best sampling scheme selection in multi-channel wireless networks, (v) the proposal of a new metric (traffic intensity) which estimates the busyness of channels by taking into consideration not only the successfully received packets but also corrupt or broken packets, (vi) implementation of time-based sampling in a prototype traffic sensor device for multi-channel traffic sensing in IEEE 802.11 b/g networks, and (vii) characterization of a campus IEEE 802.11 network environment in a spatio-temporal–spectral fashion using sampled traffic traces collected by traffic sensors.

The use of Bayesian Networks has been extended to a different scenario compared to those considered in the first year. Specifically, we studied their application to cognitive admission control in VoIP over IEEE 802.11 networks. In a paper we will present at GLOBECOM 2011, we address the problem of provisioning Quality of Service (QoS) to Voice over IP applications in a Wireless LAN scenario based on the IEEE 802.11 standard. We propose the use of a Cognitive Network approach to design a Call Admission Control (CAC) scheme, according to which each user stores relevant information on its past network experience and then uses such information to build a Bayesian Network (BN), a probabilistic graphical model to describe the statistical relationships among network parameters. The BN is exploited to predict the voice call quality, as a function of the Link Layer conditions in the particular scenario considered. Such prediction on the present and future values of the QoS provided is directly exploited to design the cognitive CAC scheme, which is shown to significantly outperform state of the art CAC techniques in a realistic scenario.

In our work on autonomous Cognitive Access Point (CogAP), we presented an application of the Cognitive Networking paradigm to the problem of development of autonomous cognitive networking solutions for small scale wireless network environments such as Wi-Fi hotspots and home networks. In these environments we typically use only one AP per service provider/residence for providing wireless services to the users. However, note that larger number of APs from multiple service providers/residences vie for bandwidth in any geographic region. Our CogAP can reduce the cost of autonomic network control

by co-location, i.e., equipping the same AP with a cognitive functionality. Such a co-location of cognitive capability faces a set of resource constraints that range from processor, memory, and cognitive algorithmic complexity. We proposed an architectural framework for autonomous CogAP and introduced our algorithmic solutions, in which two graphical models can be employed; a Neural Network-based traffic predictor and a BN-based graphical model. These models make use of historical traffic traces to learn network traffic conditions and predict traffic loads on each of 802.11 b/g channels. The cognitive decision engine makes use of traffic forecasts to dynamically decide which channel is best for CogAP to operate on for serving its clients. One of the challenges in autonomous cognitive decision making is the computation resource constraints in today's embedded APs. To prove the feasibility of our solution, we developed a prototype CogAP device using cognitive software modules and off-the-shelf hardware components. The performance evaluation of the proposed CogAP system by conducting experimental measurements on our testbed platform showsthat the proposed CogAP is effective in achieving performance enhancements with respect to state-of-the-art channel selection strategies. One live demo of CogAP was conducted at IEEE Infocom 2010 and a second demo at IEEE Globecom 2010.

Within the Subcontract awarded to the research group at the University of Padova, the research work has focused on the use of the CalRadio platform (developed at UCSD/CalIT2) for cognitive networking applications, and on network management issues in a cognitive networking context. These are key ingredients in order to make the overall system work, and the work done has provided seminal contributions to the field.

In our ACM IWCMC 2010 paper, we have proposed CRABSS, the CalRAdio-Based advanced Spectrum Scanner, which is an open platform developed to monitor the ISM band at 2.4 GHz and to reveal opportunities for a better utilization of the available spectrum resources. CRABSS is built through a modular approach by integrating the development platform CalRadio 1 with the Unified Link Layer API (ULLA) framework. This solution provides sensing capabilities while preserving the 802.11b standard compatibility on the CalRadio 1 platform. Moreover, it takes advantage of the ULLA framework to export spectrum occupancy information to prospective cognitive radio manager engines, through a standardized set of sensing APIs. The developed tool has the ability to detect spectrum occupancy, with the potential to also identify the technology being used (e.g., ZigBee vs. Bluetooth, vs. IEEE 802.11), and is therefore a useful tool on which cognitive behaviors can be built.

Management tools are very important for the success of cognitive networking systems in a decentralized environment such as the one we are considering in this project. It is of fundamental importance to be able to set up a network on the fly, in the presence of a dynamic environment and of dynamic resource availability. In addition, it is very important that such mechanisms be robust to natural impairments, as well as to intentional attacks. In our Aug. 2010 IEEE Transactions on Wireless Communications paper, we have proposed and thoroughly analyzed a new concept of Common Control Channel that, instead of being implemented on a fixed frequency, is based on random encounters among nodes that hop between the various available frequency channels. Although this concept had been explored in the past, we greatly enhanced it by using Network Coding to boost the data dissemination performance on the channel, making it much more efficient than traditional schemes. By using such control channel, cognitive users are able to quickly set up a network and to negotiate channel occupancy in a totally distributed but collision-free manner. In our Aug. 2010 IEEE Wireless Communications magazine paper, we have applied similar concepts to the neighbor discovery problem, which is one of the most fundamental ingredients of distributed networking, and a key consideration in military settings. The problem to be solved is to make it possible for a node to understand who is present in the network, in order to give them a means to coordinate and to opportunistically access the spectrum resources. Another key consideration in such phase of network setup is to make this mechanism robust against interference and intentional jamming (e.g., meant to disrupt the network setup itself), an issues of obvious relevance to tactical scenarios. The proposed scheme is able to avoid occupied channels based on opportunistic detection of channel occupancies, as well as to withstand the loss of packets due to randomly hopping jammers, and has been shown by extensive numerical evaluations to be able to provide very good networking performance. As a first step, our work focused on single-hop network scenarios, and an interesting future direction is the extension of this work to multi-hop networks.

In our paper presented at SECON 2011, we have continued our prior work on broadcasting in a multichannel environment in the presence of adversaries. More specifically, we proposed an analytical framework to study broadcasting performance in multi channel wireless networks in the presence of adversary attacks. In order to reduce the effect of such attacks on the dissemination performance we used network coding and showed that it can bring significant benefits to the broadcasting process. We investigated the impact that different medium access, transmission schemes and channel conditions have on the information exchange among all nodes. We analyzed such impact in terms of reception delay and robustness with respect to malicious interference generated by adversary nodes. In order to do so, we modeled the process of data broadcasting as a coupon collector’s problem. We derived the average delay required to retrieve partial and complete information by all nodes in the network, and quantified the gains obtained when using a multi channel system. We took into account the presence of different types of adversaries and found the optimum number of channels that nodes have to access in order to minimize the data reception delay.

In a similar multichannel environment we also performed another study, that will be presented at GLOBECOM 2011. Random access techniques have traditionally been used for the design of efficient medium access control protocols for wireless

networks where the entire bandwidth is provided to the users as a single channel to be accessed for communication. In our GLOBECOM paper we analyze the broadcast performance of several random access techniques in a multi channel system, where users can dynamically access portions of the available bandwidth at a given time and location. In order to compare these protocols we focus on metrics of interest such as the receiving probability, the system throughput and the network blocking probability. Our results show that these protocols can offer significant improvements in terms of increased system throughput provided that their operational parameters are carefully tuned to achieve near-optimal behavior in a multi channel setting.

We also performed a more theoretical study, related to cognitive interference management in retransmission-based wireless networks. Cognitive radio methodologies have the potential to dramatically increase the throughput of wireless systems. In our work, control strategies which enable the superposition in time and frequency of primary and secondary user transmissions are explored in contrast to more traditional sensing approaches which only allow the secondary user to transmit when the primary user is idle. In this work, the optimal transmission policy for the secondary user when the primary user adopts a retransmission based error control scheme is investigated. The policy aims to maximize the secondary users' throughput, with a constraint on the throughput loss and failure probability of the primary user. Due to the constraint, the optimal policy is randomized, and determines how often the secondary user transmits according to the retransmission state of the packet being served by the primary user. The resulting optimal strategy of the secondary user is proven to have a unique structure. In particular, the optimal throughput is achieved by the secondary user by concentrating its transmission, and thus its interference to the primary user, in the first transmissions of a primary user packet. The rather simple framework considered in this paper highlights two fundamental aspects of cognitive networks that have not been covered so far: (i) the networking mechanisms implemented by the primary users (error control by means of retransmissions in the considered model) react to secondary users' activity; (ii) if networking mechanisms are considered, then their state must be taken into account when optimizing secondary users' strategy, i.e., a strategy based on a binary active/idle perception of the primary users' state is suboptimal. This work has been accepted for publication in the IEEE Transactions on Information Theory.

We also extended the scope of our approach to study the challenges in gathering network traffic information from an emergency response network, in a paper presented at ICADWT 2011. We discussed the non-invasive traffic sensing and analyzing infrastructure that we created and used for a real-world application. Then, we presented some of the performance observations made using our infrastructure. Network performance measurement and analysis is a challenging task for a large-scale emergency response network. We developed an infrastructure for non-invasive traffic monitoring that requires neither modifications to nor knowledge about the production emergency response network. Our non-invasive network measurement infrastructure was used for real-world emergency response drills such as the Golden Eagle drill conducted at California State University, San Marcos in May 2010. Performance observations obtained from our system show that non-invasive traffic monitoring is a scalable, efficient, and viable method for large-scale network monitoring and performance measurement.

On the same line, we studied also the impact of physical world events on the communication activity seen in the cyber world. In the paper presented in ACWR'11, we show three physical world events where we conducted passive network traffic measurements to study the interaction between physical and cyber worlds. We consider the following types of events: an active shooter drill, a science festival scenario, and an emergency response drill involving a simulated dirty bomb attack. The network behavior during these events is contrasted with the regular network behavior. In some events, we observed substantial drop in network traffic whereas in some others, we noticed high traffic surge. Therefore, the deviation observed in the cyber world activity may be exploited to automate the detection of physical world events. The drills also involved setting up of wireless mesh network infrastructure to assist first responders in their rescue operations and provide Internet connectivity to attendees of science festival. Our passive network measurements provided valuable insights which would help us in configuring wireless mesh network testbeds more efficiently and thereby providing efficient coordination of the response activity and saving human lives and properties.

Technology Transfer

A research proposal on Cognitive Opportunistic Communications and Cognitive Cross-layer Protocol Stack Design

Grant number: W911NF-09-1-0456

Authors: Ramesh Rao, B.S. Manoj and Michele Zorzi

(4) Statement of the problem studied

The specific aims of the project include: (i) to propose a Cognitive Network concept by applying the cognition loop both to the in-stack (from MAC to Transport layer) and the out-stack parameters using probabilistic graphical models and (ii) to create opportunistic solutions for cross layer cognitive networking. We propose to use a novel approach based on Bayesian Networks (BNs) that can capture the dependency between network protocol parameters across the stack exploiting the historical behavior of the observed data.
We also proposed and prototyped a Cognitive Access Point (CogAP) that utilized the out-stack BN model. Furthermore, we investigated cross layer solutions for implementing a distributed control channel and a neighbor discovery mechanism that is robust against jamming attacks, studying the problem both with a theoretical and a simulative approach. We concluded our work with a practical case of study, in which we observed the challenges in gathering network traffic information from an emergency response network and we studied three physical world events where we conducted passive network traffic measurements to study the interaction between physical and cyber worlds.

(5) Summary of the most important results

In our work on the application of cognition loop on the protocol stack, published in the proceedings of IEEE GLOBECOM 2010 and IEEE MILCOM 2010, we used a probabilistic graphical modeling approach, Bayesian Networks (BNs), in order to create a representation of the dependency relationships between significant parameters spanning transport and medium access control (MAC) layers in single-hop and multi-hop wireless network environments. We made two key contributions: first, in single-hop networks, we created graphical models from historical data observed from the protocol stack and verified their usefulness and second, we created a BN consists of MAC and transport parameters and used that BN graph to estimate the possibility of network congestion. That is, we exploit our BN models to face one of the problems of the TCP protocol, which does not have any mechanism to infer when congestion occurs in the network and therefore waits till some packets are lost for reacting to congestion in the network. Such a reactive nature of TCP leads to wastage of precious network resources like bandwidth

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The contributions of this work include the following: (i) a discussion of packet sampling techniques for traffic sensing in multi-channel wireless networks, (ii) a comparison of various time-based sampling strategies using the Kullback–Leibler divergence (KLD) measure, (iii) a study on the effect of the sampling parameters on the accuracy of the sampling strategies, (iv) development of sampling accuracy graphs for easing the process of best sampling scheme selection in multi-channel wireless networks, (v) the proposal of a new metric (traffic intensity) which estimates the busyness of channels by taking into consideration not only the successfully received packets but also corrupt or broken packets, (vi) implementation of time-based sampling in a prototype traffic sensor device for multi-channel traffic sensing in IEEE 802.11 b/g networks, and (vii) characterization

of a campus IEEE 802.11 network environment in a spatio-temporal–spectral fashion using sampled traffic traces collected by traffic sensors.

The use of Bayesian Networks has been extended to a different scenario compared to those considered in the first year. Specifically, we studied their application to cognitive admission control in VoIP over IEEE 802.11 networks. In a paper we will present at GLOBECOM 2011, we address the problem of provisioning Quality of Service (QoS) to Voice over IP applications in a Wireless LAN scenario based on the IEEE 802.11 standard. We propose the use of a Cognitive Network approach to design a Call Admission Control (CAC) scheme, according to which each user stores relevant information on its past network experience and then uses such information to build a Bayesian Network (BN), a probabilistic graphical model to describe the statistical relationships among network parameters. The BN is exploited to predict the voice call quality, as a function of the Link Layer conditions in the particular scenario considered. Such prediction on the present and future values of the QoS provided is directly exploited to design the cognitive CAC scheme, which is shown to significantly outperform state of the art CAC techniques in a realistic scenario.

In our work on autonomous Cognitive Access Point (CogAP), we presented an application of the Cognitive Networking paradigm to the problem of development of autonomous cognitive networking solutions for small scale wireless network environments such as Wi-Fi hotspots and home networks. In these environments we typically use only one AP per service provider/residence for providing wireless services to the users. However, note that larger number of APs from multiple service providers/residences vie for bandwidth in any geographic region. Our CogAP can reduce the cost of autonomic network control by co-location, i.e., equipping the same AP with a cognitive functionality. Such a co-location of cognitive capability faces a set of resource constraints that range from processor, memory, and cognitive algorithmic complexity. We proposed an architectural framework for autonomous CogAP and introduced our algorithmic solutions, in which two graphical models can be employed; a Neural Network-based traffic predictor and a BN-based graphical model. These models make use of historical traffic traces to learn network traffic conditions and predict traffic loads on each of 802.11 b/g channels. The cognitive decision engine makes use of traffic forecasts to dynamically decide which channel is best for CogAP to operate on for serving its clients. One of the challenges in autonomous cognitive decision making is the computation resource constraints in today's embedded APs. To prove the feasibility of our solution, we developed a prototype CogAP device using cognitive software modules and off-the-shelf hardware components. The performance evaluation of the proposed CogAP system by conducting experimental measurements on our testbed platform showsthat the proposed CogAP is effective in achieving performance enhancements with respect to state-of-the-art channel selection strategies. One live demo of CogAP was conducted at IEEE Infocom 2010 and a second demo at IEEE Globecom 2010.

Within the Subcontract awarded to the research group at the University of Padova, the research work has focused on the use of the CalRadio platform (developed at UCSD/CalIT2) for cognitive networking applications, and on network management

issues in a cognitive networking context. These are key ingredients in order to make the overall system work, and the work done has provided seminal contributions to the field.

In our ACM IWCMC 2010 paper, we have proposed CRABSS, the CalRAdio-Based advanced Spectrum Scanner, which is an open platform developed to monitor the ISM band at 2.4 GHz and to reveal opportunities for a better utilization of the available spectrum resources. CRABSS is built through a modular approach by integrating the development platform CalRadio 1 with the Unified Link Layer API (ULLA) framework. This solution provides sensing capabilities while preserving the 802.11b standard compatibility on the CalRadio 1 platform. Moreover, it takes advantage of the ULLA framework to export spectrum occupancy information to prospective cognitive radio manager engines, through a standardized set of sensing APIs. The developed tool has the ability to detect spectrum occupancy, with the potential to also identify the technology being used (e.g., ZigBee vs. Bluetooth, vs. IEEE 802.11), and is therefore a useful tool on which cognitive behaviors can be built.

Management tools are very important for the success of cognitive networking systems in a decentralized environment such as the one we are considering in this project. It is of fundamental importance to be able to set up a network on the fly, in the presence of a dynamic environment and of dynamic resource availability. In addition, it is very important that such mechanisms be robust to natural impairments, as well as to intentional attacks. In our Aug. 2010 IEEE Transactions on Wireless Communications paper, we have proposed and thoroughly analyzed a new concept of Common Control Channel that, instead of being implemented on a fixed frequency, is based on random encounters among nodes that hop between the various available frequency channels. Although this concept had been explored in the past, we greatly enhanced it by using Network Coding to boost the data dissemination performance on the channel, making it much more efficient than traditional schemes. By using such control channel, cognitive users are able to quickly set up a network and to negotiate channel occupancy in a totally distributed but collision-free manner. In our Aug. 2010 IEEE Wireless Communications magazine paper, we have applied similar concepts to the neighbor discovery problem, which is one of the most fundamental ingredients of distributed networking, and a key consideration in military settings. The problem to be solved is to make it possible for a node to understand who is present in the network, in order to give them a means to coordinate and to opportunistically access the spectrum resources. Another key consideration in such phase of network setup is to make this mechanism robust against interference and intentional jamming (e.g., meant to disrupt the network setup itself), an issues of obvious relevance to tactical scenarios. The proposed scheme is able to avoid occupied channels based on opportunistic detection of channel occupancies, as well as to withstand the loss of packets due to randomly hopping jammers, and has been shown by extensive numerical evaluations to be able to provide very good networking performance. As a first step, our work focused on single-hop network scenarios, and an interesting future direction is the extension of this work to multi-hop networks.

In our paper presented at SECON 2011, we have continued our prior work on broadcasting in a multichannel environment in the presence of adversaries. More

specifically, we proposed an analytical framework to study broadcasting performance in multi channel wireless networks in the presence of adversary attacks. In order to reduce the effect of such attacks on the dissemination performance we used network coding and showed that it can bring significant benefits to the broadcasting process. We investigated the impact that different medium access, transmission schemes and channel conditions have on the information exchange among all nodes. We analyzed such impact in terms of reception delay and robustness with respect to malicious interference generated by adversary nodes. In order to do so, we modeled the process of data broadcasting as a coupon collector's problem. We derived the average delay required to retrieve partial and complete information by all nodes in the network, and quantified the gains obtained when using a multi channel system. We took into account the presence of different types of adversaries and found the optimum number of channels that nodes have to access in order to minimize the data reception delay.

In a similar multichannel environment we also performed another study, that will be presented at GLOBECOM 2011. Random access techniques have traditionally been used for the design of efficient medium access control protocols for wireless networks where the entire bandwidth is provided to the users as a single channel to be accessed for communication. In our GLOBECOM paper we analyze the broadcast performance of several random access techniques in a multi channel system, where users can dynamically access portions of the available bandwidth at a given time and location. In order to compare these protocols we focus on metrics of interest such as the receiving probability, the system throughput and the network blocking probability. Our results show that these protocols can offer significant improvements in terms of increased system throughput provided that their operational parameters are carefully tuned to achieve near-optimal behavior in a multi channel setting.

We also performed a more theoretical study, related to cognitive interference management in retransmission-based wireless networks. Cognitive radio methodologies have the potential to dramatically increase the throughput of wireless systems. In our work, control strategies which enable the superposition in time and frequency of primary and secondary user transmissions are explored in contrast to more traditional sensing approaches which only allow the secondary user to transmit when the primary user is idle. In this work, the optimal transmission policy for the secondary user when the primary user adopts a retransmission based error control scheme is investigated. The policy aims to maximize the secondary users' throughput, with a constraint on the throughput loss and failure probability of the primary user. Due to the constraint, the optimal policy is randomized, and determines how often the secondary user transmits according to the retransmission state of the packet being served by the primary user. The resulting optimal strategy of the secondary user is proven to have a unique structure. In particular, the optimal throughput is achieved by the secondary user by concentrating its transmission, and thus its interference to the primary user, in the first transmissions of a primary user packet. The rather simple framework considered in this paper highlights two fundamental aspects of cognitive networks that have not been covered so far: (i) the networking mechanisms implemented by the primary users (error control by means of retransmissions in the considered model) react to secondary users' activity; (ii) if

networking mechanisms are considered, then their *state* must be taken into account when optimizing secondary users' strategy, *i.e.*, a strategy based on a binary active/idle perception of the primary users' state is suboptimal. This work has been accepted for publication in the IEEE Transactions on Information Theory.

We also extended the scope of our approach to study the challenges in gathering network traffic information from an emergency response network, in a paper presented at ICADWT 2011. We discussed the non-invasive traffic sensing and analyzing infrastructure that we created and used for a real-world application. Then, we presented some of the performance observations made using our infrastructure. Network performance measurement and analysis is a challenging task for a large-scale emergency response network. We developed an infrastructure for non-invasive traffic monitoring that requires neither modifications to nor knowledge about the production emergency response network. Our non-invasive network measurement infrastructure was used for real-world emergency response drills such as the Golden Eagle drill conducted at California State University, San Marcos in May 2010. Performance observations obtained from our system show that non-invasive traffic monitoring is a scalable, efficient, and viable method for large-scale network monitoring and performance measurement.

On the same line, we studied also the impact of physical world events on the communication activity seen in the cyber world. In the paper presented in ACWR'11, we show three physical world events where we conducted passive network traffic measurements to study the interaction between physical and cyber worlds. We consider the following types of events: an active shooter drill, a science festival scenario, and an emergency response drill involving a simulated dirty bomb attack. The network behavior during these events is contrasted with the regular network behavior. In some events, we observed substantial drop in network traffic whereas in some others, we noticed high traffic surge. Therefore, the deviation observed in the cyber world activity may be exploited to automate the detection of physical world events. The drills also involved setting up of wireless mesh network infrastructure to assist first responders in their rescue operations and provide Internet connectivity to attendees of science festival. Our passive network measurements provided valuable insights which would help us in configuring wireless mesh network testbeds more efficiently and thereby providing efficient coordination of the response activity and saving human lives and properties.

(6) Bibliography

(1) Submissions or publications under ARO sponsorship **during this reporting period**. List the title of each and give the total number for each of the following categories:
(a) Papers published in peer-reviewed journals

1. N. Baldo, A. Asterjadhi, M. Zorzi, "Dynamic spectrum access using a network coded cognitive control channel," IEEE Trans. on Wireless Commun., vol. 9, n. 8, pp. 2575-2687, Aug. 2010
2. A. Asterjadhi, M. Zorzi, "JENNA: A Jamming Evasive Network-coding Neighbor-discovery Algorithm for Cognitive Radio Networks," IEEE Wireless Communications Magazine, Special Issue on Dynamic Spectrum Access, August 2010.

3. R. Manfrin, A. Zanella, M. Zorzi "CRABSS: CalRAdio-Based advanced Spectrum Scanner for cognitive networks" Wiley's Journal on Wireless Communications and Mobile Computing, vol . 10, n. 12, Dec. 2010, pp. 1682-1695.
4. M. Levorato, U. Mitra, M. Zorzi, "Cognitive Interference Management in Retransmission-Based Wireless Networks", accepted for publication in the IEEE Trans. on Information Theory, 2011.
5. C. K. Verma, B. R. Tamma, B. S. Manoj, and R. Rao, "A Realistic Small-World Model for Wireless Mesh Networks," in IEEE Communications Letters, Vol. 15, n. 4, Aprile 2011
6. B. R. Tamma, B.S. Manoj, and R. Rao, "Traffic Sensing and Characterization in Multi-channel Wireless Networks for Cognitive Networking", accepted for publication in Elsevier Computer Networks.

(b) Papers published in non-peer-reviewed journals
(c) Presentations

i. Presentations at meetings, but not published in Conference Proceedings

1. We presented a poster and a live demo of CogAP at the the IEEE Infocom 2010, held during April 2010. (An abstract for the poster/demo will appear in IEEE Infocom 2011 proceedings with the following citation information: B. R. Tamma, B. S. Manoj, and Ramesh Rao, "CogAP: An Autonomous Cognitive Access Point for Wi-Fi Hotspots," IEEE INFOCOM 2010 Demonstrations, San Diego, March 2010.)
2. NSF sponsored Wireless National TestBed (WiNTeB), held during May 5-6th, 2010.
3. A poster and a presentation delivered at the Center for Wireless Communications Bi-annual presentations at UCSD, May 2010.
4. Our proposal for a demonstration titled "A Cognitive Access Point using Bayesian Networks," was accepted at IEEE Globecom 2010 scheduled to be held during December 6-10, 2010.

ii. Non-Peer-Reviewed Conference Proceeding publications (other than abstracts)

iii. Peer-Reviewed Conference Proceeding publications (other than abstracts)

1. B. R. Tamma, B. S. Manoj, and R. R. Rao, "An Autonomous Cognitive Access Point for Wi-Fi Hotspots," in Proceedings of IEEE Globecom 2009, November-December 2009.
2. Yao Liu, B. R. Tamma, B. S. Manoj, and R. R. Rao, "Traffic Prediction for Cognitive Networking in Multi-Channel Wireless Networks," Proceedings of IEEE INFOCOM-2010 Workshop on Cognitive Wireless Communications and Networking 2010, April 2010.

3. R. Manfrin, L. Boscato, A. Zanella, M. Zorzi "CRABSS: CalRAdio-Based advanced Spectrum Scanner for cognitive networks" Invited paper. In proceedings of the 6th ACM International Wireless Communications and Mobile Computing Conference (IWCMC 2010), June 28-July 2, 2010.
4. G. Quer, S. N. H. Meenakshisundaram, B. R. Tamma, B. S. Manoj, R. R. Rao, and M. Zorzi, “Cognitive Network Inference through Bayesian Network Analysis,” in the Proceedings of IEEE MILCOM 2010, October-November 2010.
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11. B.S. Manoj, T. Bheemarjuna Reddy, and Ramesh R. Rao, "On the Impact of Physical-Cyber world Interactions during Unexpected Events", Accepted for publication in Proc. of International Conference on Wireless Technologies for Humanitarian Relief (ACWR2011), December 2011.
12. G. Quer, N. Baldo and M. Zorzi, “Cognitive Call Admission Control for VoIPover IEEE 802.11 using Bayesian Networks,” Accepted for publication in the Proceedings of IEEE Globecom 2011.
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